

Technical-economic optimization of the storage
and distribution of electricity with solar origin

SYSTRA

JALON 3- S8 (P5E702)

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1. Introduction

The project presented throughout this report consists on technical-economic study of a system composed by a solar park connected to a set of batteries. The software chosen to represent all the components of the studied system has been Matlab-Simulink which allows us to carry realistic simulations in different scenarios.

For every part of the system, an initial research on the information of the component has been carried out with the objective of deeply understanding how it works, its concrete role in the system and what parameters might influence it. In addition to this, an electrical model of the component has been chosen (which will be the one used later in Simulink). Finally, a Simulink model has been created in order to simulate different scenarios and situations. The models will be as realistic as possible with the objective of properly representing the reality.

Different user scenarios have been studied once the whole Simulink model has been developed. The objective is not only to model the system but also to optimize economically the interactions between the user (company or individual) and the global grid. The Simulink model will provide plenty of information of the system including a precise tracking of the purchased and sold power which maximizes profit (or minimizes the losses).

2. The system

As it has been presented in the introduction the system studied consists of a solar park connected to a set of batteries (Figure 1). In this section, every component of the system will be analysed and then its Simulink model will be explained.

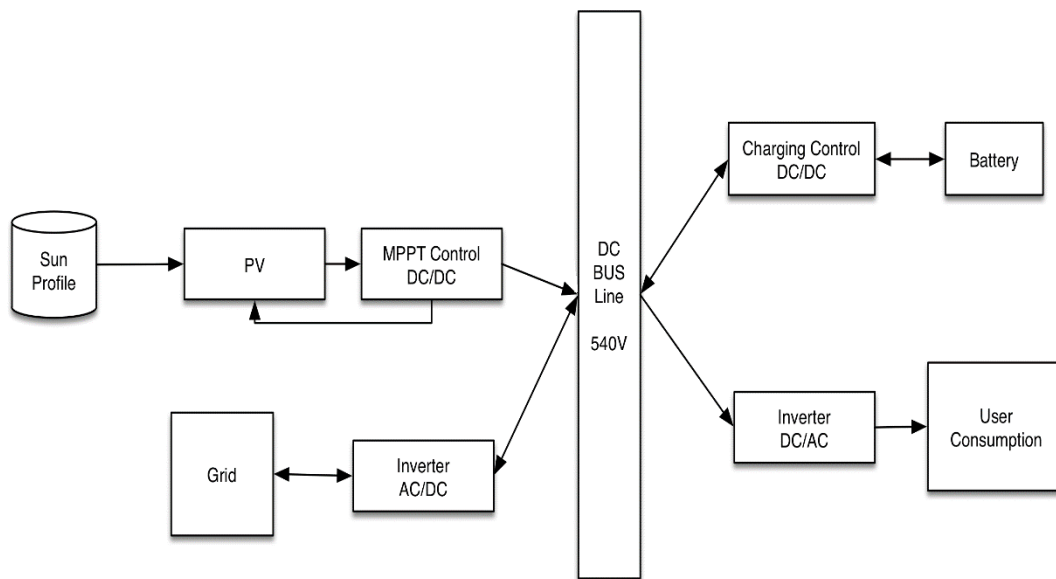


Figure 1. Solar park connected to a set of batteries (all components involved).

2.1 Solar panel or photovoltaic (PV) module

The solar panel is a main part of our system. It is the component which allows us to reduce the price of electricity using the batteries.

2.1.1 Theoretical principle on a PV module

Solar panels absorb the sunlight as a source of energy to generate electricity. A photovoltaic (PV) module is a packaged, connect assembly of photovoltaic cells. The semi-conductor's proprieties are used to produce electricity. The main principle is based on a p-n junction. This kind of junction has some interesting properties that have useful applications in modern electronics, for example, in producing electricity in a solar panel.

In a solar cell, we make a P-N junction with two pieces of semi-conductor's materials: one of type P and another of type N.

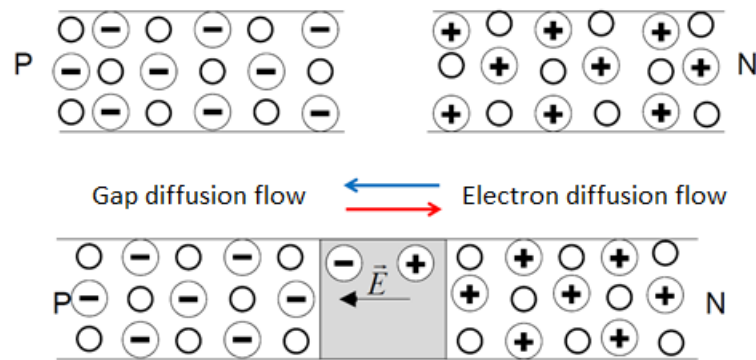


Figure 2. P-N junction.

The gaps from the semiconductors P get diffused to the semiconductors N and the electrons go from the N material to the P.

There are many recombinations that make the mobile porters disappear in the central zone. There are only the fix ions left. The fix ions create an electric intern field E opposed to what made it appear, which are the minor porters, which leads to an equilibrate state.

The electric field E creates a potential difference V_0 between the N region and the P region called potential barrier. V_0 depends on the concentration n_i of free electrons in the material, and on the N_a number of acceptors atoms in the P region and on the N_d number of atoms in the N region that can be given to the P region.

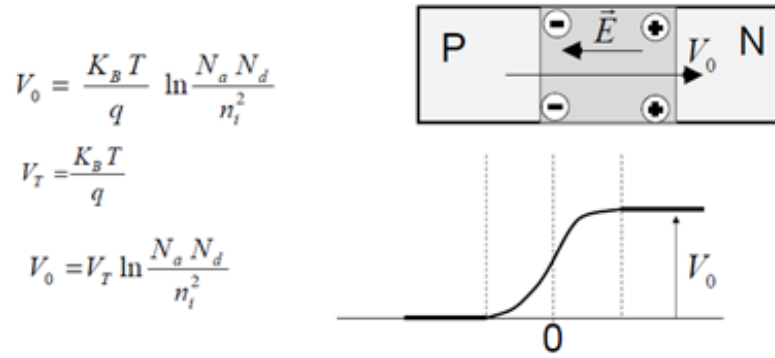


Figure 3. P-N junction and tension and electric inside.

Where:

- K_B is the Boltzmann constant (1.381×10^{-23} J/K).
- q is the electron charge (1.602×10^{-19} C).
- T is the cell temperature

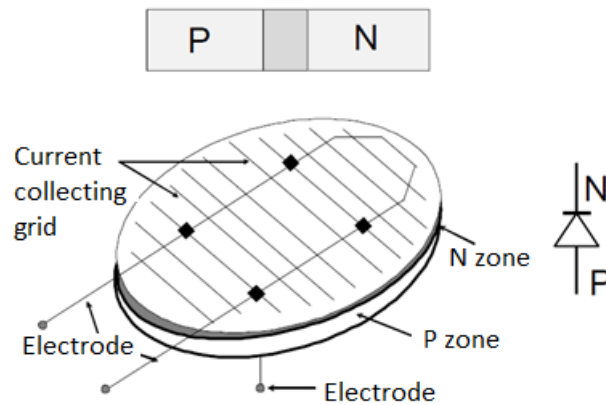


Figure 4. PV cell.

Whenever a photon enters the charge zone and hits an atom, if the photon's energy is high enough the atom releases an electron. The energy of an atom is $E = h \nu$, where h is the Planck constant and ν the photon's frequency.

The electric field makes a force to this electron and pushes it to the N zone. The current appears.

2.1.2 Electric model

The PV electrical model used is the following:

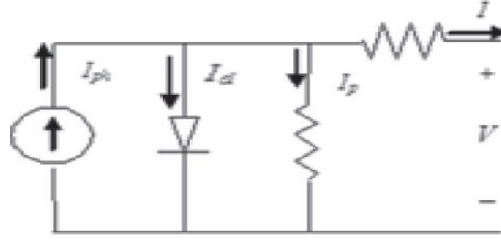


Figure 5. PV electric model.

By applying Kirchhoff's laws we obtain:

$$I = I_{ph} - I_d - I_p$$

Where I_{ph} is the photocurrent, I_d is the diode current and I_p is the current leak in the parallel resistor. The next steps will develop the expression of these three intensities. The **diode current** (I_d) is proportional to the saturation current which is given by:

$$I_d = I_0 \left[\exp \left(\frac{V}{A \cdot N_s \cdot V_T} \right) - 1 \right]$$

In this equation we can find several parameters:

- V_T is the voltage imposed on the diode and its expression is: $V_T = k \cdot T_c / q$.
- I_0 is the reverse saturation or leakage current of the diode (A).
- T_c is the cell temperature (we assume 25°C).
- k is the Boltzmann constant (1.381×10^{-23} J/K).
- q is the electron charge (1.602×10^{-19} C). N_s is the number of PV cells connected in series.
- We define the modified ideality factor $a = N_s \cdot A \cdot k \cdot T_c / q = N_s \cdot A \cdot V_T$.

Afterwards, we calculate the **current leak in the parallel resistor** (I_p). By applying the Ohm's law, we find that $I_p = (V + R_s \cdot I) / R_p$.

The last current to calculate is the photocurrent. The expression of I_{ph} is:

$$I_{ph} = \frac{G}{G_{ref}} (I_{ph,ref} + \mu_{sc} \cdot \Delta T)$$

The parameters appearing in this equation are the following:

- G is the irradiance [W/m^2].
- G_{ref} is de irradiance at short circuit ($1000 W/m^2$).
- $\Delta T = T_c - T_{c_ref}$, where T_{c_ref} is the cell temperature at short circuit (298 K).
- μ_{sc} is the coefficient temperature of short circuit current, in our case it is $3.18 \cdot 10^{-3}$ (from the PV cell datasheet).
- I_{ph_ref} is the photocurrent [A] at short circuit.

With:

$$I_{ph,ref} \approx I_{sc,ref}$$

If we apply the equations of I_d , I_p and I_{ph} to initial Kirchhoff's equation we can easily find:

$$I = I_{ph} - I_0 \left[\exp \left(\frac{V + I \cdot R_s}{a} \right) - 1 \right] - \frac{V + R_s I}{R_p}$$

The last calculus we need to carry out is finding I_0 with the expression that follows:

$$I_0 = I_{0,\text{ref}} \left(\frac{T_c}{T_{c,\text{ref}}} \right)^3 \exp \left[\left(\frac{q \&G}{A \cdot K} \right) \left(\frac{1}{T_{c,\text{ref}}} - \frac{1}{T_c} \right) \right]$$

And the expression of $I_{0,\text{ref}}$ is:

$$I_{0,\text{ref}} = I_{sc,\text{ref}} \exp \left(\frac{-V_{oc,\text{ref}}}{a} \right)$$

2.1.3 Simulink model

These are the equations we will apply to our Simulink model. The model is the following:

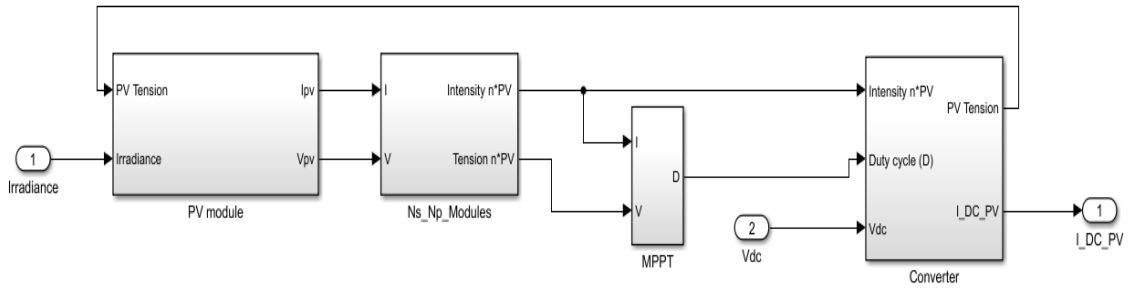


Figure 6. General view of the PV cell Simulink model.

Let's focus on the PV module and see each part separately.

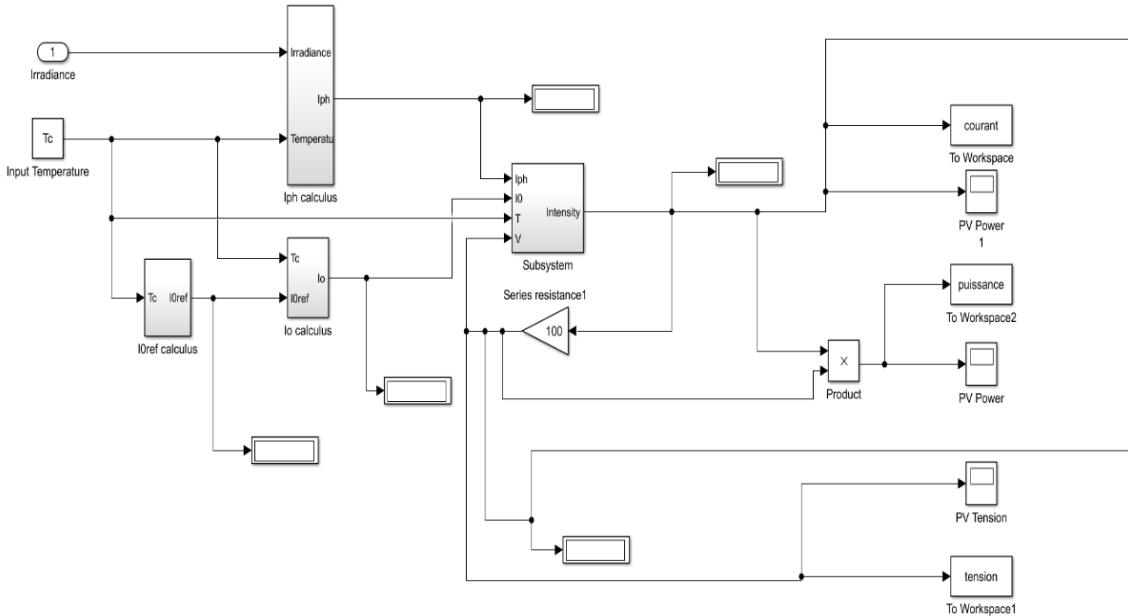


Figure 7. General view of the PV cell Simulink model and its components.

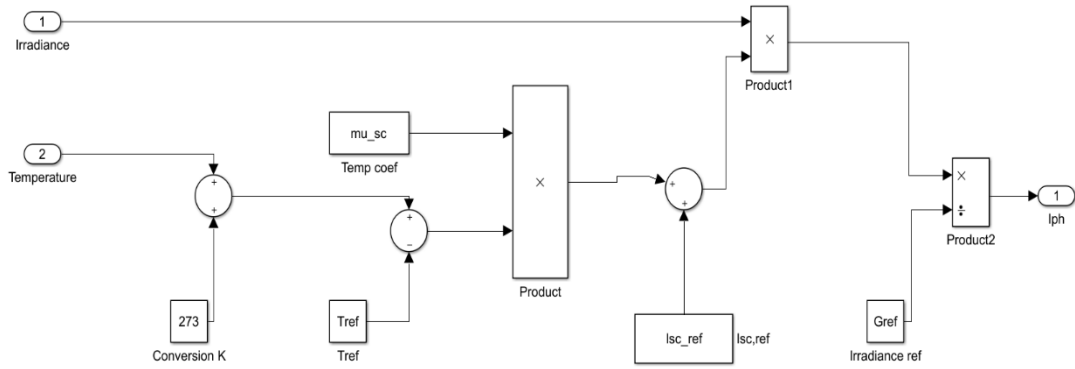


Figure 8. I_{ph} calculus

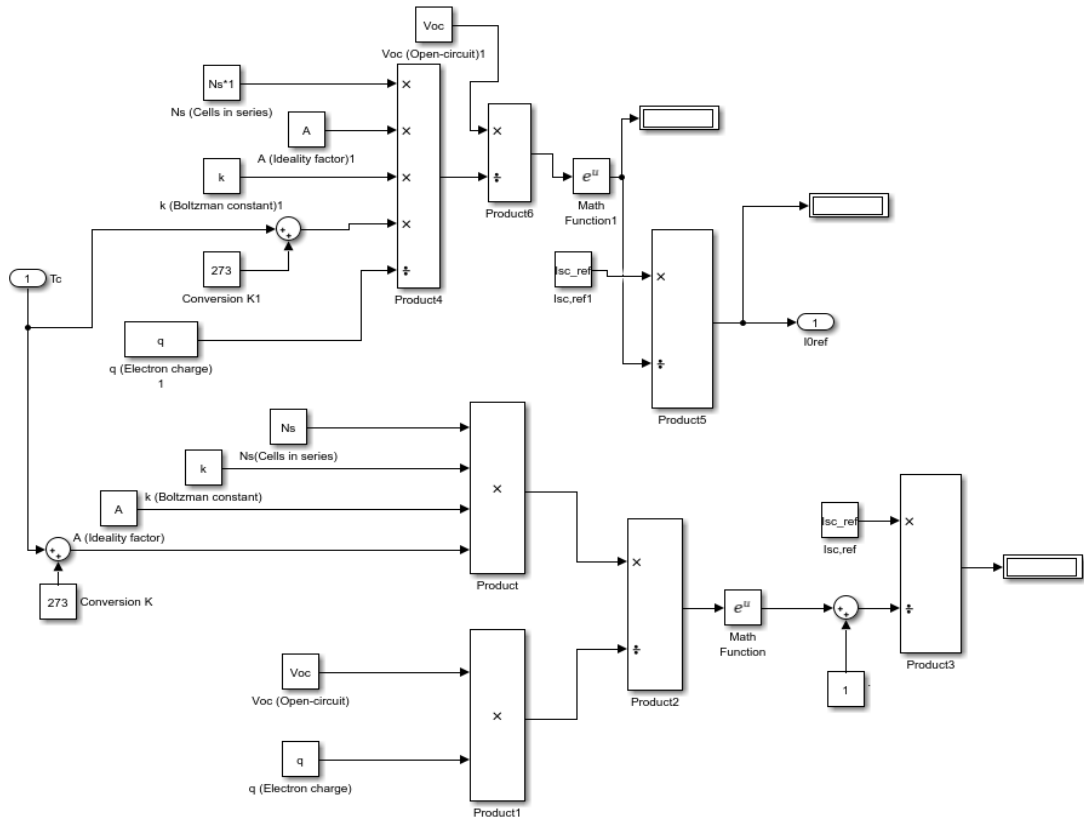


Figure 9. I_{0ref} calculus.

2.1.4 Verification of Simulink model

This is the Simulink model exactly how we make it and use it. There are a lot of displays and scopes to observe each value obtained and find the mistakes when there was. The next plots were used to prove that our model was correct.

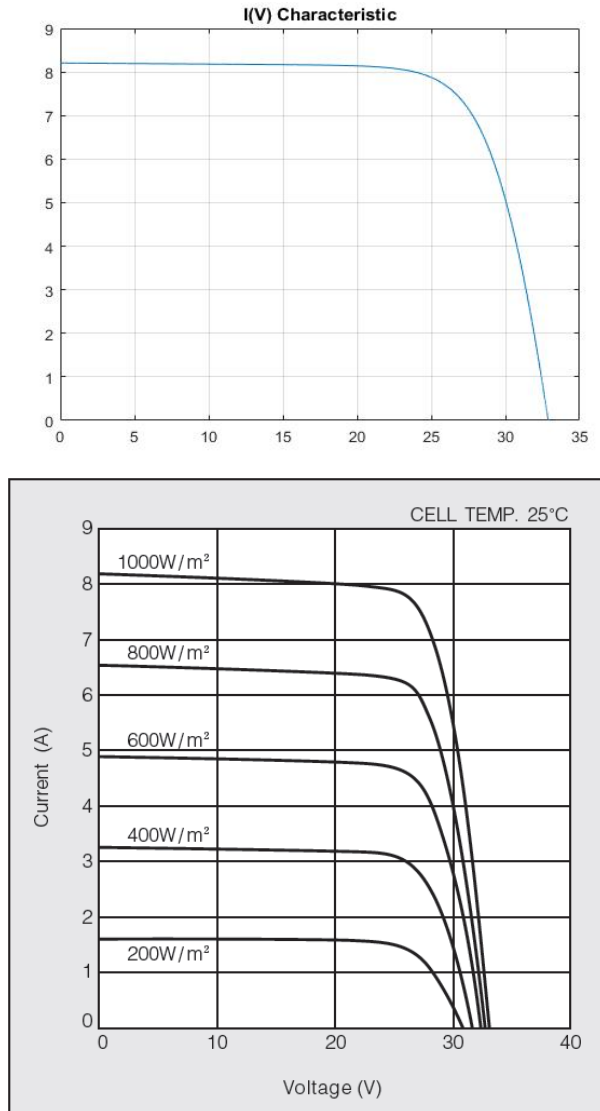


Figure 12. $I(V)$ characteristic for a constant irradiation of 1000 W/m^2 and a variable charge resistance. We compare our own model with the characteristic given by the data sheet of the PV KC200GT

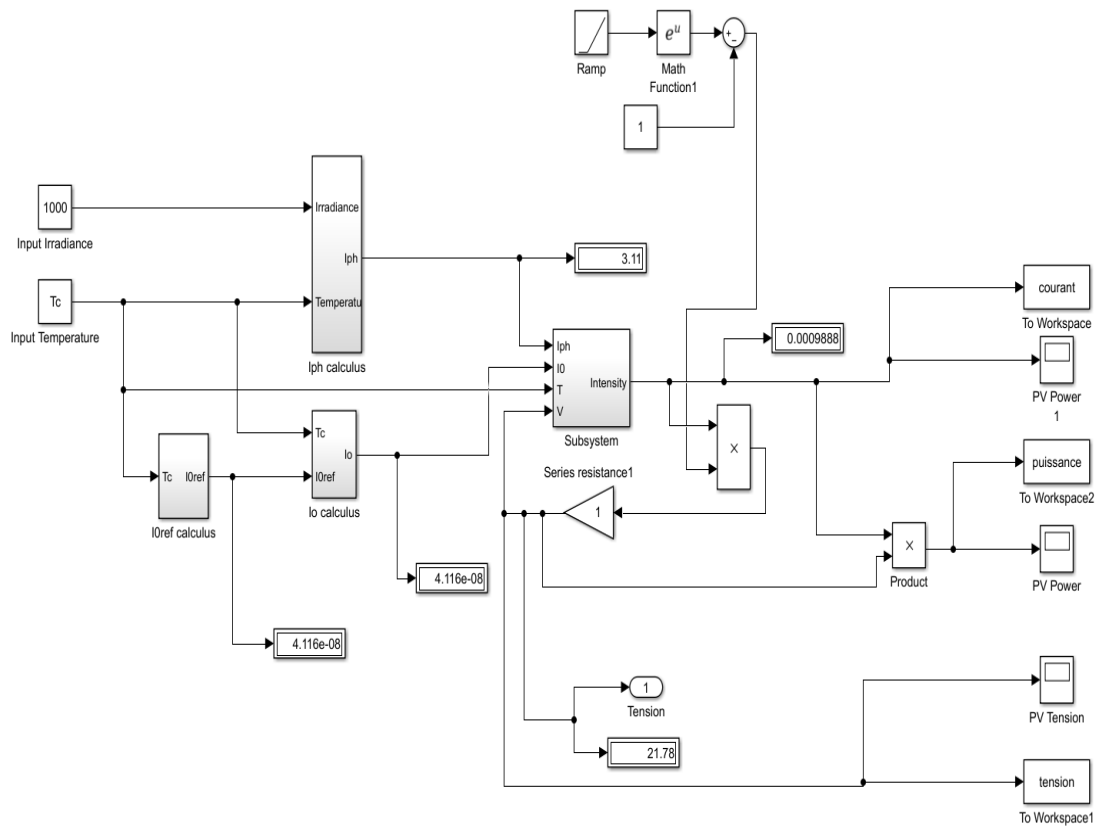


Figure 13. Simulink model used to obtain the characteristic models above.

2.1.5 Solar irradiance

The Simulink model used to analyse the solar irradiance with a profile depending in the time of the day is the following:

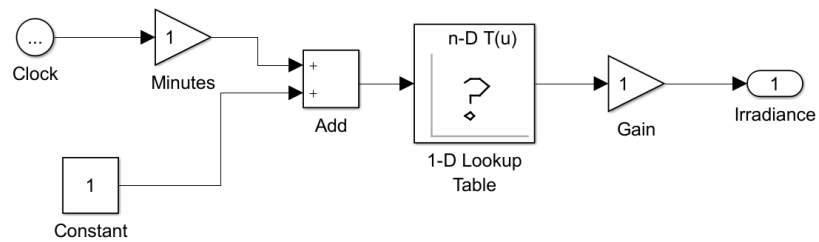


Figure 14. Solar irradiance Simulink model.

2.2 MPPT

Collecting the renewable energy is not enough, we also have to increase the efficiency and the quality of the RES and that's the reason why we have to use MPPT strategy. MPPT stands for maximum power point tracking and it has been widely used in practice.

Take the solar panel system as an example. The variation in solar irradiance (G) or temperature (T) results in nonlinear I–V and P–V characteristic curves. At any time, there exists a unique maximum power point (MPP) that fluctuates continuously as G or T varies. Due to this dynamic, a maximum power point tracker (MPPT) is needed to ensure maximum power is extracted by the dc-dc converter under any environmental condition. To achieve this objective, the MPPT algorithm is designed to match the MPP with the converter operating voltage and current.

Over the years, there are numerous MPPT strategies having been proposed and the P&O (perturb and observe) is the most popular due its simplicity and fast response. The goal of the P&O algorithm is to find the operating point as close as possible to the MPP by climbing the slope of the P–V curve. First, it calculates the power () by sensing the voltage () of the PV array, then it provides a perturbation (φ) in V, based on the change of power. In Figure 15 we can observe the MPPT algorithm.

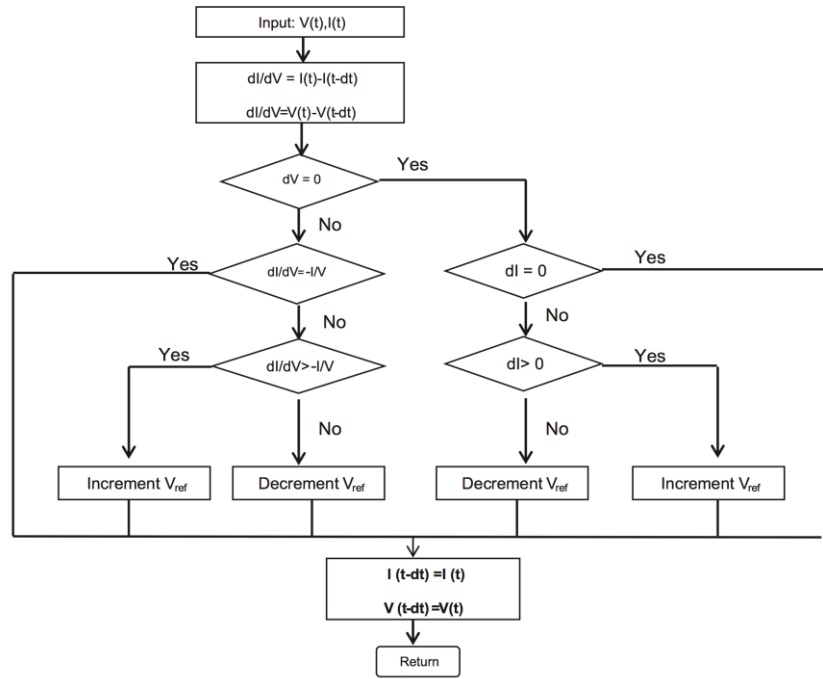


Figure 15. MPPT algorithm.

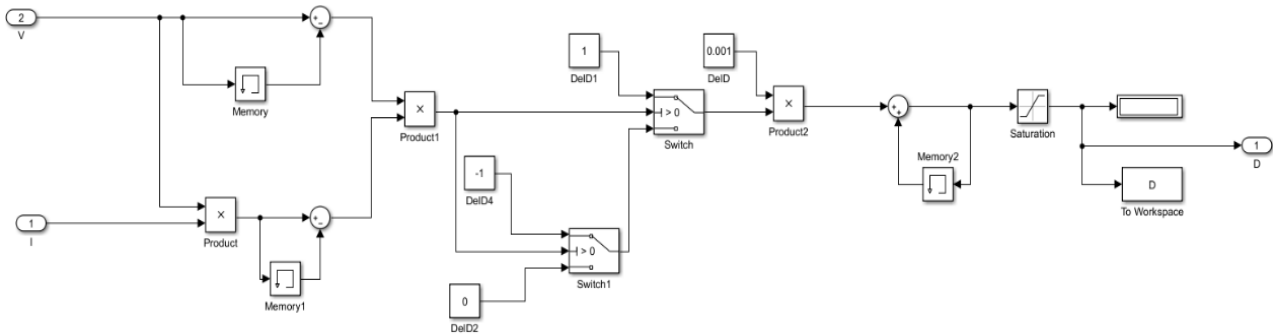


Figure 16. Simulink MPPT model.

2.3 Battery

2.3.1 Electric model

The electric model used to represent the battery is the one shown in Figure 16. Its transfer function is the following: $I = (V - OCV) * (Cd * Rs - 1/s) / [Cd * Rd * Rs + (Rs + Rd)/s]$

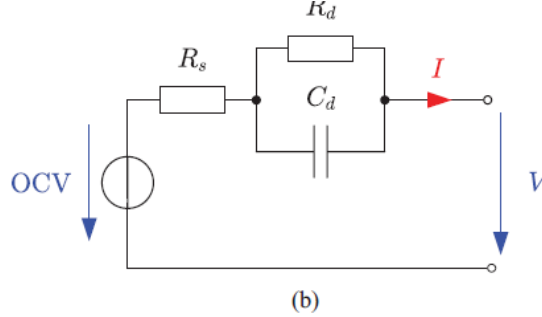


Figure 17. Electric model of a Li-Ion battery.

The component of the model above are the following: OCV stands for the open circuit voltage, R_s represents the resistance of the contacts, R_d and C_d are the resistance and the capacitance characterizing the transient response of the battery cell electrodes.

Once we have calculated the intensity, another important parameter is the state of charge (SOC). We can easily calculate the SOC for our model with the following equations:

$$SOC = SOC_{ini} - (C - Q)/C$$

Where C is the available charge in a fully charged battery cell. Q can be calculated as follows:

$$Q = \int_0^{t_0} I(t) dt$$

It is important to highlight that the values of OCV, R_d , R_s and C_d depend on the SOC value as has been experimentally proved. The exact relationship between OCV and SOC for a Li-Ion battery is:

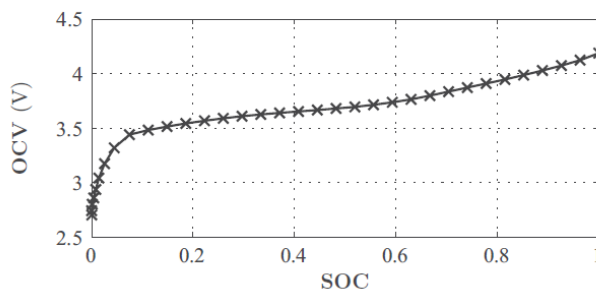


Figure 18. Linear interpolation of the measured OCV at a different SOC for the Li-Ion battery.

In the case of R_s , R_d and C_d , it exists a linear relationship between them and SOC as we appreciate in Figure 15. In the figure there are two battery model but the one which is pertinent with our study is LIM2.

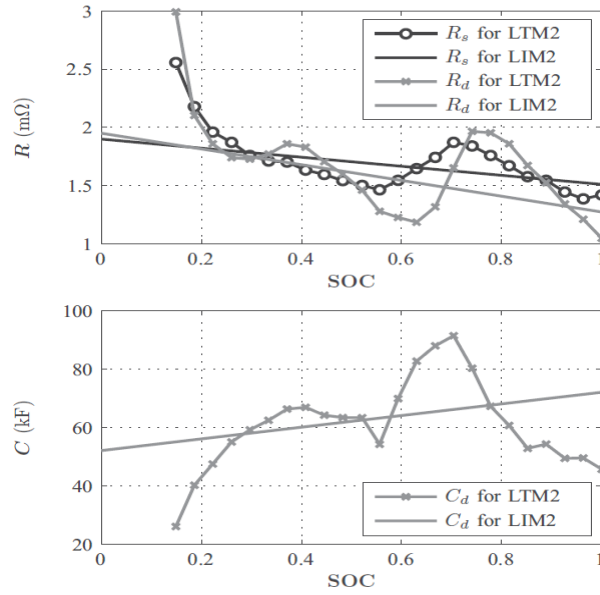


Figure 19. Relationship between R_s , R_d and C_d and SOC for the Li-Ion battery.

This will be the model used in Simulink to represent the behaviour of battery. The rest of the parameters which are used in the model have been taken from a real data sheet of a Li-Ion battery in order to make the problem as realistic as possible (*Battery Model: LIR18650 2600mAh*).

2.3.2 Simulink model

With all this calculus we can obtain the Simulink model. The general model of our system is:

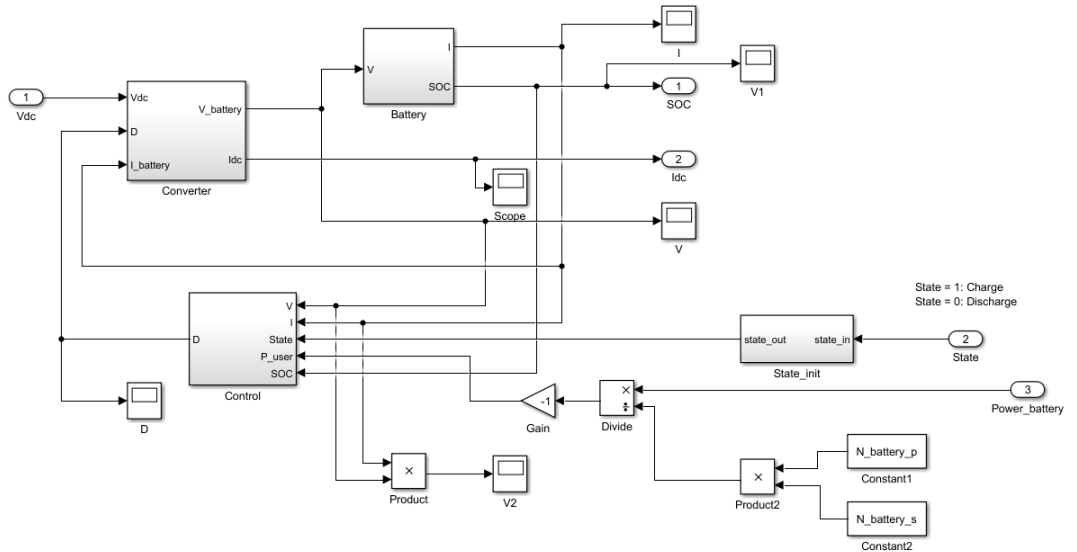


Figure 20. General view of the Simulink model of a battery (with the converter and the controller).

2.4 DC/DC Converter

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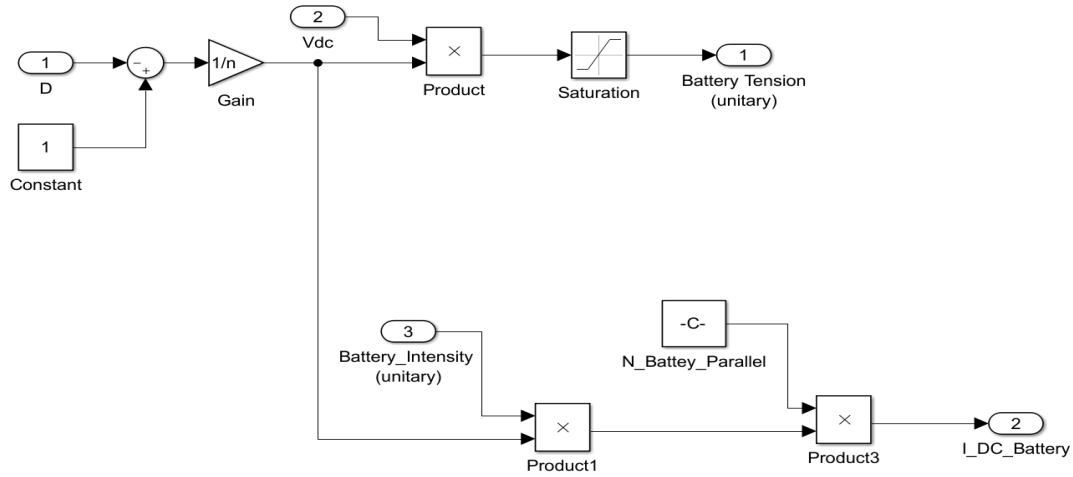


Figure 23. DC/DC converter Simulink model for battery model.

2.5 AC/DC Inverter

The inverter is used for transfer the alternate current into the direct current. More than this, it can also transfer the direct current back to alternate current for selling the electricity.

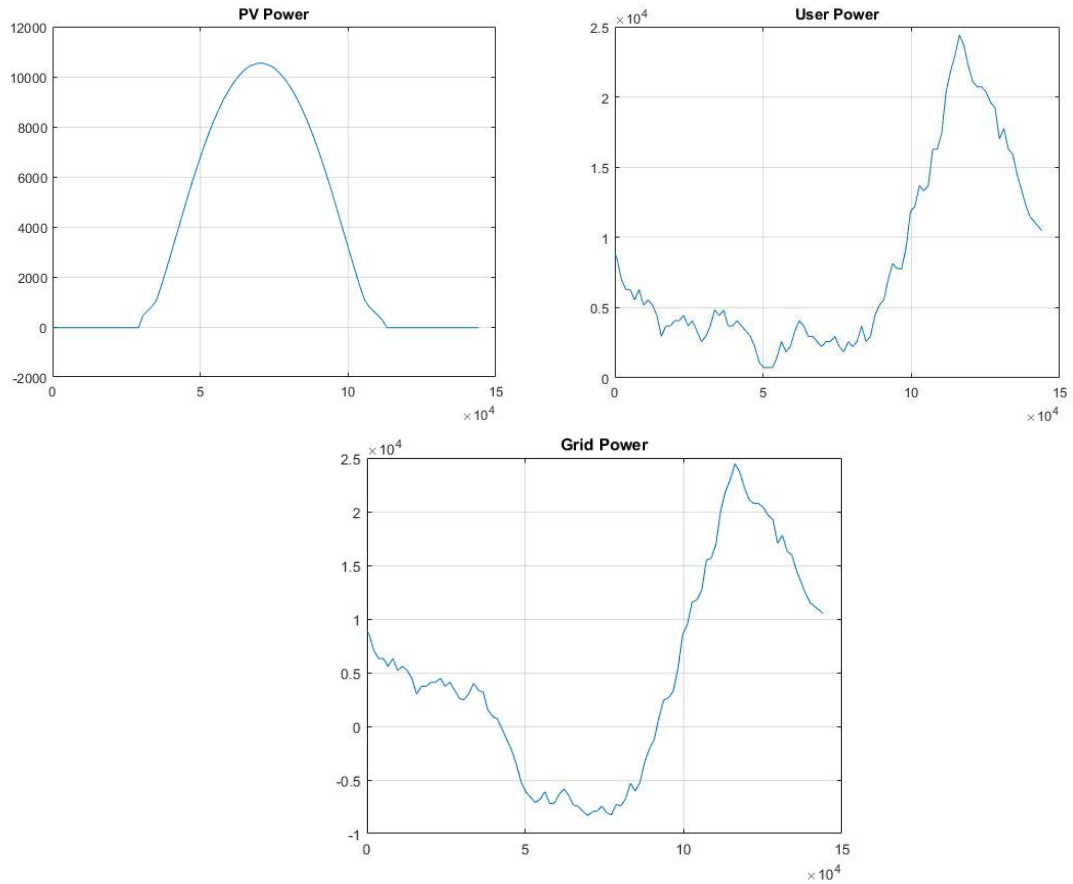
2.6 DC Bus Line

The bus line is used for connecting all the components and make it easier and more practical to extend. Usually the voltage of bus line is depended on the scale of the whole system. Here we choose 540V as a medium-scale. The voltage is maintained by the grid and every component that connects to the bus line has to adapt to this constant voltage.

2.7 Grid

The grid in RES is considered as a supplemental component to fill the vacancy when there is no wind and sun. However, with the help of bidirectional AC/DC converter, RES can also sell the extra energy to the grid and increase the profitability.

In our model we compute the exchanges of power between the user and the grid. If P_{grid} is positive at a moment t then we are buying power from the grid. On the other hand, if P_{grid} is negative, then we are selling power to the grid. Here is a simple example of the interaction with the grid (we won't use batteries in this model so that it is easy to see that $P_{Grid}=P_{User}-P_{Sun}$):



2.8 User

The type of user's consumption is not specific. It can be a community or it can be electrical vehicles park. But in general, it is just a part to consume the energy produced by the RES. So we have to give the consumption previously and tested whether the RES can satisfy the needs of user.

2.9 Global system

Finally, we can find the global system:

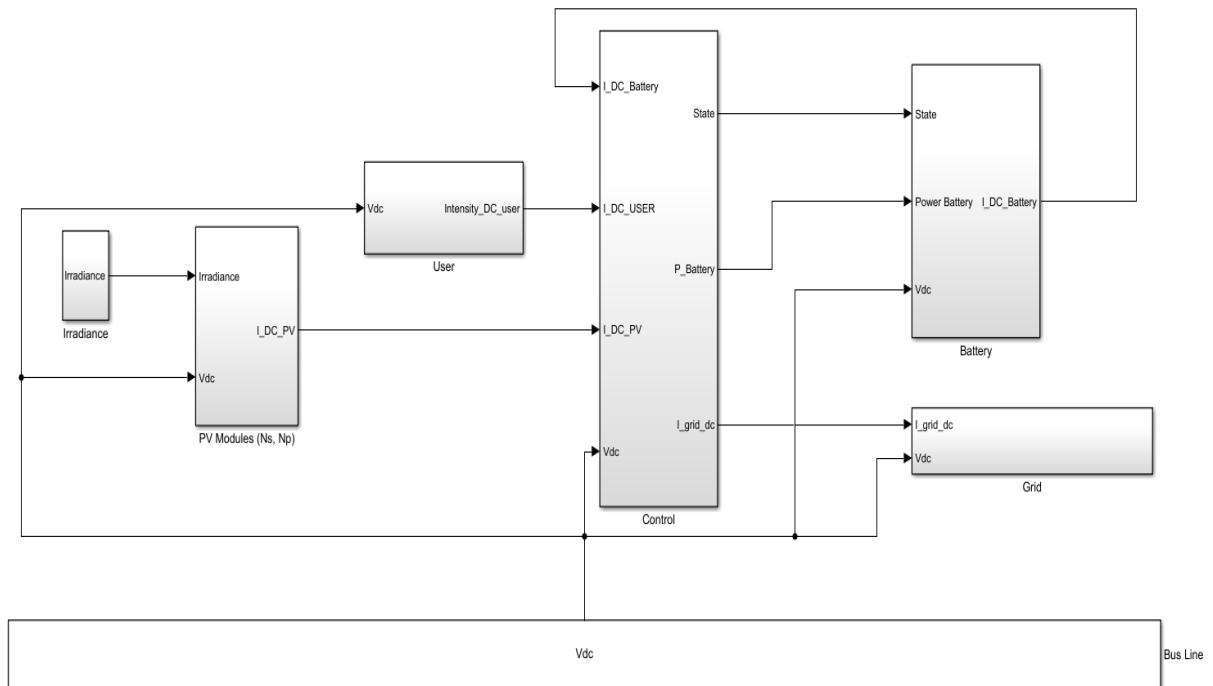


Figure 24. Complete Simulink model of the system.

3. User scenario design: A residential community in southern France

Together with the growing adoption of EVs, the technology and infrastructure to charge them are developing as well. What we want to do is to find a solution to meet the demand of extra energy with the help of solar energy. In order to determine the user's need for energy, we attempt to estimate the construct a scenario in which our ideal strategy will be examined.

Now, 90% of the time of EV is spent in the parking lot and a parking lot is also a common place where the charging points are. After reviewing the existing solutions, we found that there are mainly three kinds of places where people mostly charge their EVs:

- Home (60%)
- Working place (20%)
- Public parking lot (20%)

When people charge their EVs at home, they most do it at night after coming back home. This is what call "the night charge". And for the second option, many companies will provide charging points for their employees and this is called "the day charge". And for the third option, people can also find public charging point to charge their EVs when they need.

3.1 Where is our parking lot?

According to the research, there are more than 60% of charging points are situated at home. Therefore, it is necessary to design a scenario for the residential area if we want to have a more realistic model. Here we consider a community situated in southern France where solar energy is abundant and the people who live there mainly use EV as the tool of transportation.

3.2 How to charge?





Firstly, we look up for the standards applied in the EV charging field in France.

3.3 Charging mode

Today the only standards available at European level, dealing with the charging system, plugs, and sockets, are contained in the IEC 61851. The actual standards provide a first classification of the type of charger in function of its rated power and so of the time of recharge, defining three categories here listed:

- Normal power or slow charging, with a rated power inferior to 3,7 kW, used for domestic application or for long-time EV parking.
- Medium power or quick charging, with a rated power from 3,7 to a 22 kW, used for private and public EV.
- High power or fast charging, with a rated power superior to 22 kW, used for public EV. The mode of charging is independent of the connectors.

It is all about the communication between the car and the charging point. Different charging modes usually correspond to different charging time. The IEC 61851-1 Committee on “Electric vehicle conductive charging system” has then defined 4 Modes of charging. In function of the amount of power, different main connections are possible and they are summarized in terms of electrical ratings in the table below:

	Mode 1	Mode 2	Mode 3	Mode 4
Principle	- Direct, passive connection of the EV to the AC mains -Without extra control pins	-Active connection of the EV to the AC mains, with the addition of the control pilot to the passive components (cables)	- Active connection of the EV to a fixed EVSE	- Charging by direct current*
Schema				
Power	250 V / 16 A max 1-pahse 480 V / 16 A max 3-phase	1,8kW / 8 A max 1-pahse (no dedicated plug) or 3,2 kW / 14 A* maxi limited à 8 A par le mode 2	3,7 kW / 16A max 1-phase (standard normal charging) 22 kW / 32 A max 3-phase (accelerated normal charging)	50 kW / 120 A
Time of charging	8 – 12 h	8 – 12 h	1 - 8 h	20 – 30 min
Type of charging	Not recommended for charging EV (absence of required earthing)	Slow charge	Standard normal charging Accelerated normal charging	Rapid charging
Security	No dedicated plugs, do the security depends on the situation of the electrical installation.			The external charger converter AC/DC integrates the control and the electrical protection.

*Mode 4 is an ultra-fast charge using an external battery charger.

Figure 25. Different charging methods.

3.4 Plugs

IEC 62196 Plugs, socket-outlets, vehicle couplers and vehicle inlets – Conductive charging of electric vehicles is an international standard for a set of electrical connectors for electric vehicles and is maintained by the International Electrotechnical Commission (IEC).

IEC 62196-1 is applicable to plugs, socket-outlets, connectors, inlets and cable assemblies for electric vehicles, intended for use in conductive charging systems which incorporate control means, with a rated operating voltage not exceeding:

- 690 V AC 50–60 Hz at a rated current not exceeding 250 A.
- 600 V DC at a rated current not exceeding 400 A.

3.5 How large our parking lot is? How many charging points do we need?

According to the real scale of population in Toulouse, there are 371 family in our community. And according to the prediction of the sale of EV, in the 20407, the ratio of EV sale in the French market will be around 35%. So at least, there should be 137 places of charging points. Though we have the fast charging mode and the medium charging mode, which is more efficient and rapid, for the domestic user, the slow charging mode is the most economical solution, because it doesn't require expensive adaptor. Therefore, we only provide one type of charging mode: slow mode. In the slow mode, EV can be charged at a relatively slow speed with the 3.7kW AC (Different EVs have different charging power and 3.7kw is the average charging calculated by 10 types of EV10). According to the data provided by the manufacturers, most of EV can be fully charged in 8h.

3.6 The stochastic model

Our stochastic model is designed based on the real driver behaviour. And according to the previous analysis, we can make the following assumptions:

- Only exist one mode of charging
Slow mode: 3.7kw
- The number of family: 371
- The number of EV: 130
- Utilization:
 - 1) t_{arrive} : The arriving time is a random variable which satisfies $N(18h, 1.5^2)$ (the Gaussian distribution).
 - 2) t_{leave} : The leaving time is also a random variable which satisfies $N(8h, 1.2^2)$ (the Gaussian distribution).
 - 3) t_{charge} : The charging time is a random variable which satisfies Gamma (2, 2) (the gamma distribution).
 - 4) Correction: Obviously, we have that if $t_{arrive} + t_{charge} > t_{leave}$, then $t_{charge} = t_{leave} - t_{arrive}$.
 - 5) It also exists a certain number of EVs using the charging points uniformly in a day.
- The price of electricity:
 - 7:00 - 14:00 & 17:00 - 2:00(+1): 0.156 Euro/(kw*h)
 - 14:00 - 17:00 & 2:00 - 7:00: 0.127 Euro/(kw*h)

And here is the implementation in MATLAB:

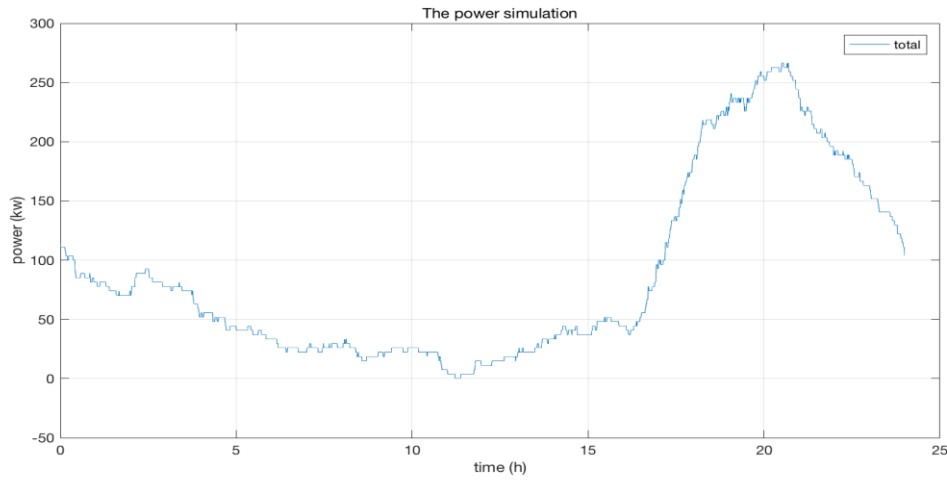


Figure 26. Matlab implementation (number of EVs and power simulation).

4. Strategy of operation

In general, we construct four concrete models to implement the strategy of operation.

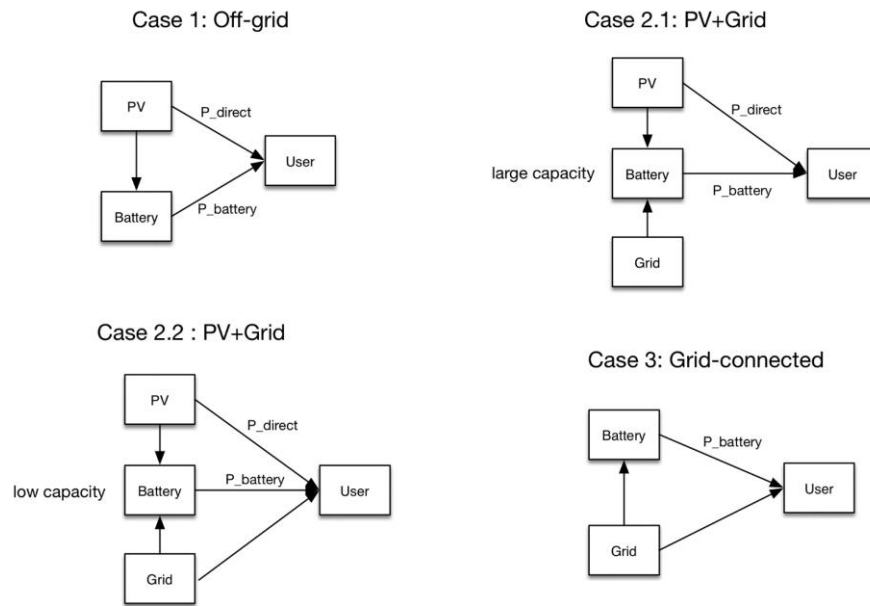


Figure 27. For models of application.

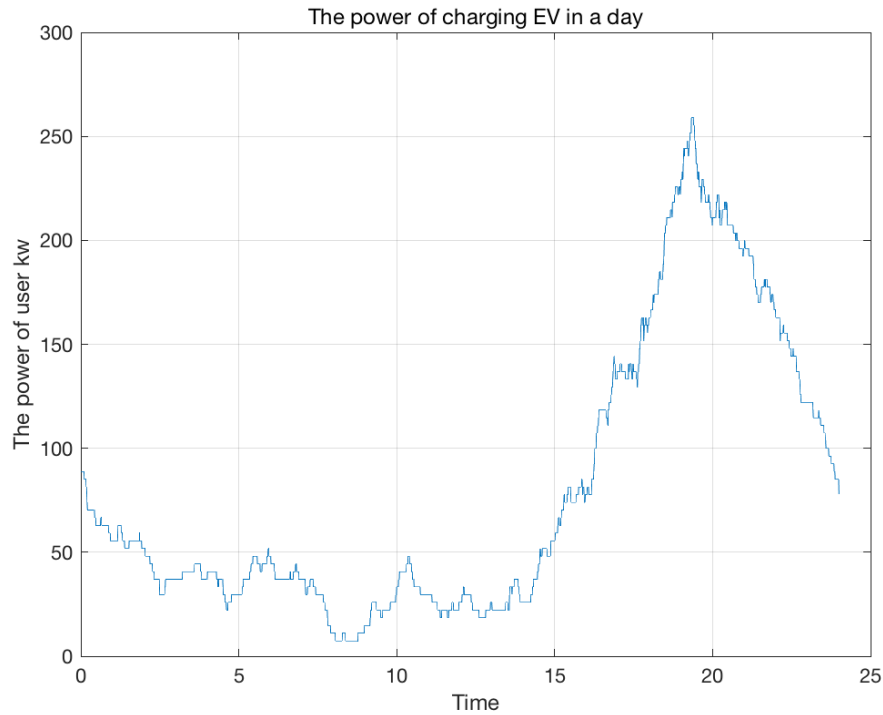
4.1 Case 1: Off-grid mode

In the first case, we want to find how to design a PV system when the system is totally independent of the grid, which means that all the energy consumed in the system come from the solar energy.

$$E_{\text{user}} = EPV$$

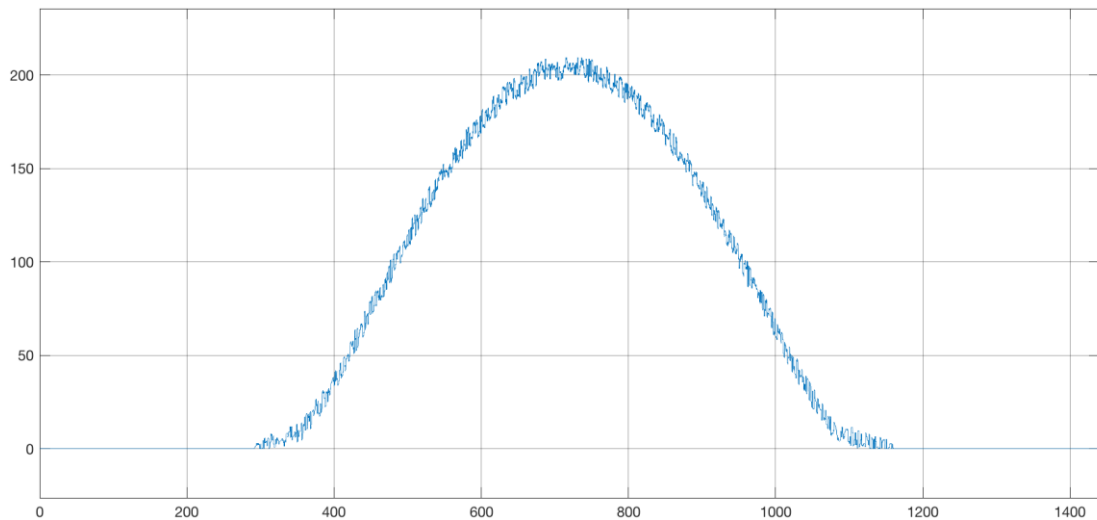
4.1.1 Determine the demand of power consumption

For a residential area that has around 100 EVs. The total energy: $6.935 \times 10^9 \text{ J} = 1926.405 \text{ kWh}$



4.1.2 Determine the minimum number of PV

The power of a single PV in a day is plotted in the following:



The total energy produced by a single PV is $5.5667 \times 10^6 \text{ J} = 1.5463 \text{ kWh}$.

So, it needs at least 1245.8 modules of PV to satisfy the needs of a day.

After considering the energy lost in the system, it has to multiply 1.45 and finally the number of PV is 1807. Total energy produced in a day is 2,794.1641 kWh

4.1.3 Energy Storage System (Battery)

Battery unit:

- Combination method: 3S 50P (150 cell)
 - Rated capacity: 100Ah
 - Working voltage: 11.1V
- Standard charged voltage: 12.6V
- Standard charged current: $0.2C = 20A$
- Maximum charged current: $1C = 100A$
- Maximum discharged current: $0.2C = 20A$

There are three criterias need to be satisfied:

1. Maximum discharge power is greater than the maximum power of user
2. Stored energy is greater than the consumption
3. Maximum charge power is greater than the maximum power of PV

- Criterion one & three

We find the maximum power of charging and discharging are:

$$P\{\text{charge_max}\} = 3.5596 \times 10^5 W$$

$$P\{\text{discharge_max}\} = 2.5900 \times 10^5 W$$

So in order to satisfy these two criterias:

$$N\{\text{battery_charge}\} = P\{\text{charge_max}\} / I\{\text{chargemax}\} \times U\{\text{charge}\} = 3.5596 \times 10^5 / 100 \times 12.6 \approx 283$$

$$N\{\text{battery_discharge}\} = P\{\text{discharge_max}\} / I\{\text{dischargemax}\} \times U\{\text{working}\} = 2.5900 \times 10^5 / 20 \times 11.1 \approx 1167$$

So at least it needs 1167 modules of battery.

- Criterion two

We also have to consider the depth of charging β , which means that we can't discharge the total energy stored in the battery in a single discharging cycle. Normally the depth of discharging is 50% and if it needs to consider the fact of life of battery, the depth of discharging can be reduced to increase battery's lifespan.

So, we can have the following formula:

$$C = E\{\text{total}\} \eta \times \beta \times U\{\text{working}\} = 1926.405 \text{ kWh} \times 0.85 \times 0.5 \times 11.1V = 4083 \times 10^3 \text{ Ah}$$

Where: C is the capacity of battery, η is the rate of energy loss, β is the depth of discharging.

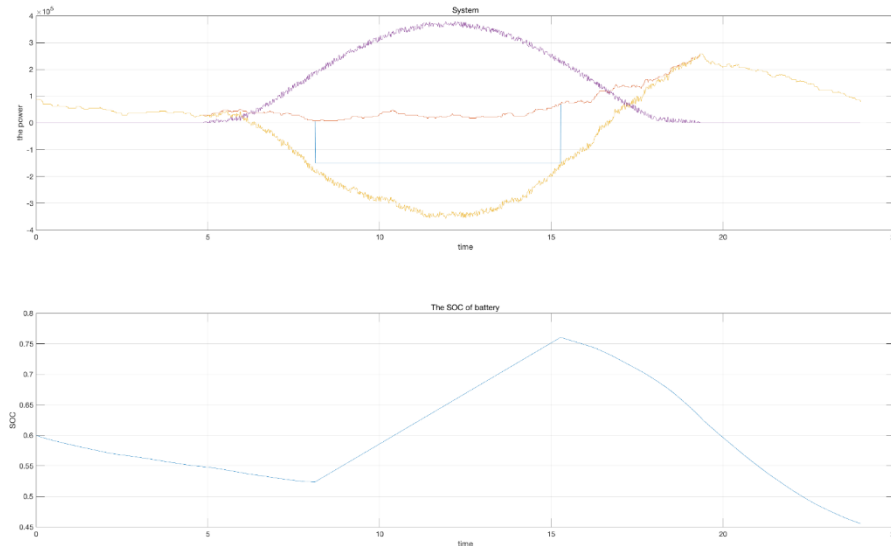
Thus, we need at least $N\{\text{bat}\} = C\{\text{unit}\} = 4083$ modules of battery in parallel.

- Conclusion:

After considering all the criteria, the system needs at 4083 modules of battery, which will cost around 590294 Euro.

4.1.4 Charging strategy

Another point we have to consider is the method of charging. Normally, a battery should be charged in a stable condition, which means the current of charging is consistent. In this case, we plot the evolution power of system in a day (blue: P_{battery} , purple: PPV, orange: P_{user} , yellow: $P_{\text{net}} = P_{\text{user}} - PPV$)

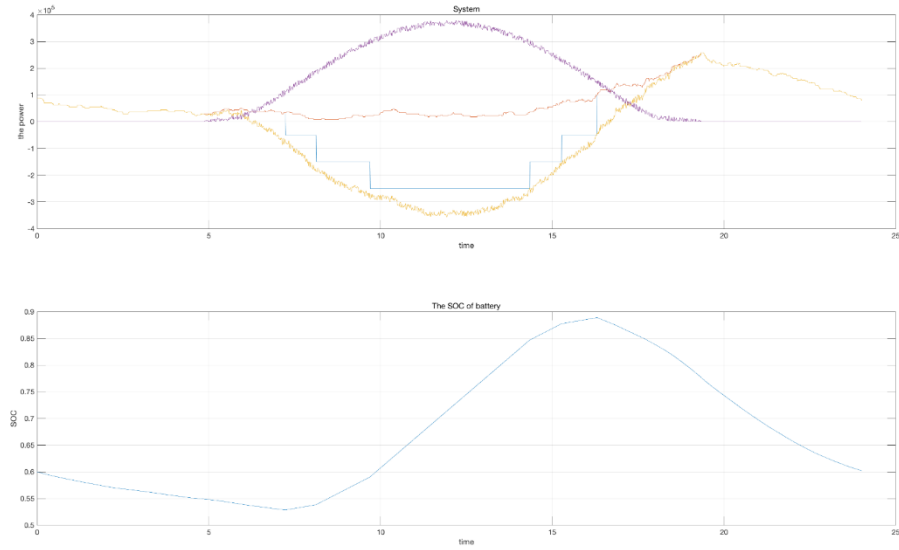


In this first simulation, we find the battery is charged when $P_{\text{net}} > P_{\text{charge}} = 150 \text{ kW}$ and nearly half of the net energy ($E_{\text{net}} = E_{\text{PV}} - E_{\text{user}}$) is wasted. The total lost energy is $5.47 \times 10^9 \text{ J} = 1521 \text{ kWh}$, which is enormous. Therefore, when we analyze the variation of SOC , at the end of day, SOC decreases to 45% which cannot be satisfied the long-term utilization.

In order to improve the efficiency of storage, we can set different levels of charging to extract the solar energy maximally. Here we set three levels:

- Low level: 50 kW
- Medium level: 150 kW
- High level: 250 kW

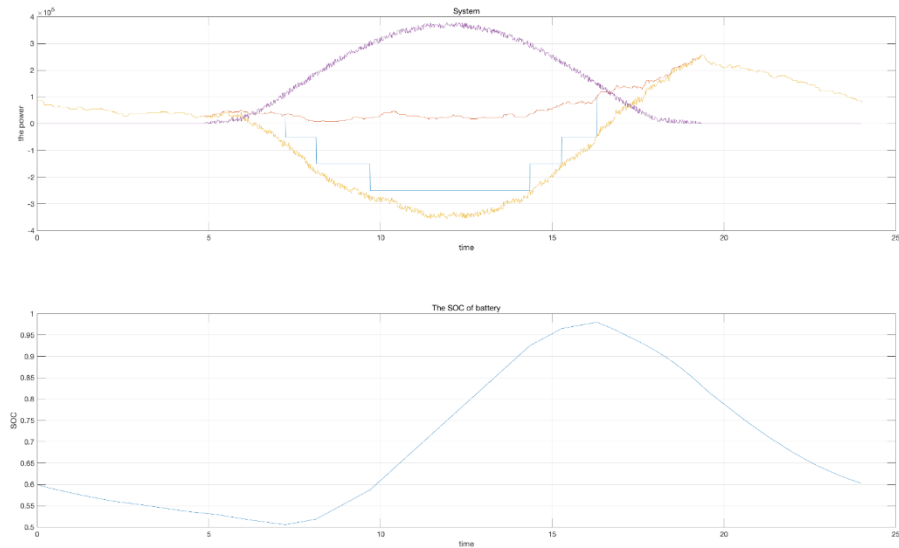
And we plot the revolution of power again:



In the second simulation, we change the pattern of charging and it increases the storage of solar energy. Finally, the total lost energy is $3.087 \times 10^9 \text{ J} = 857.57 \text{ kWh}$ which is only around half of the constant charging method. And as for the SOC curve, at the end of day, the value of SOC is 60% which perfectly matches the initial value of SOC. In this way, it is a practical system in terms of long time.

4.1.5 Amelioration

Though the previous system is practical, the maximum SOC is less than 90%, which means usage rate of battery is not closed to 100%. So, we reduce the number of battery to 3104 step by step and we have the following curve:



The maximum SOC is closed to 100% and all the other parameters are satisfied.

4.1.6 Conclusion

- Total consumption: 1926.405 kWh
- Solar energy: 2,794.1641 kWh
- Number of PV: 1807
- Capacity of battery: 3.1035×10^5 Ah
- Number of battery (100 Ah, 12V): 3104

2. Case 2: Grid-connected mode

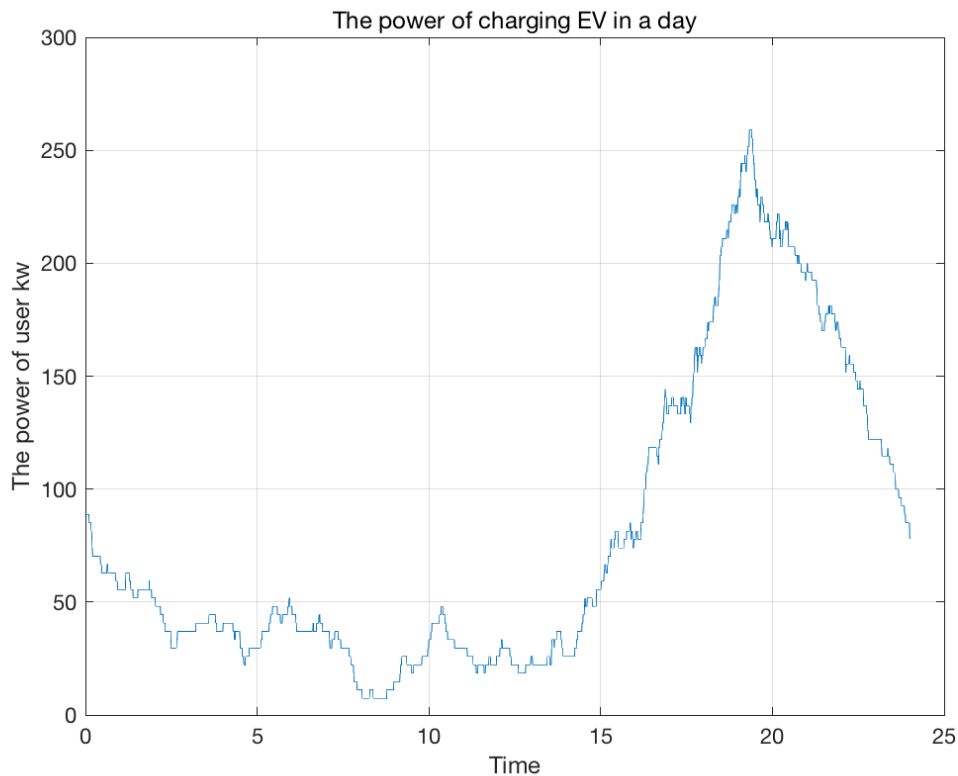
In the second case, the user scenario is the same as the case of off-grid PV system. And here we want to analyze the situation when there are only half number of PVs, which is combination of solar energy and the grid.

$$E_{\text{user}} = E_{\text{solar}} + E_{\text{grid}}$$

4.2.1 Determine the demand of power consumption

For a residential area that has around 100 EVs

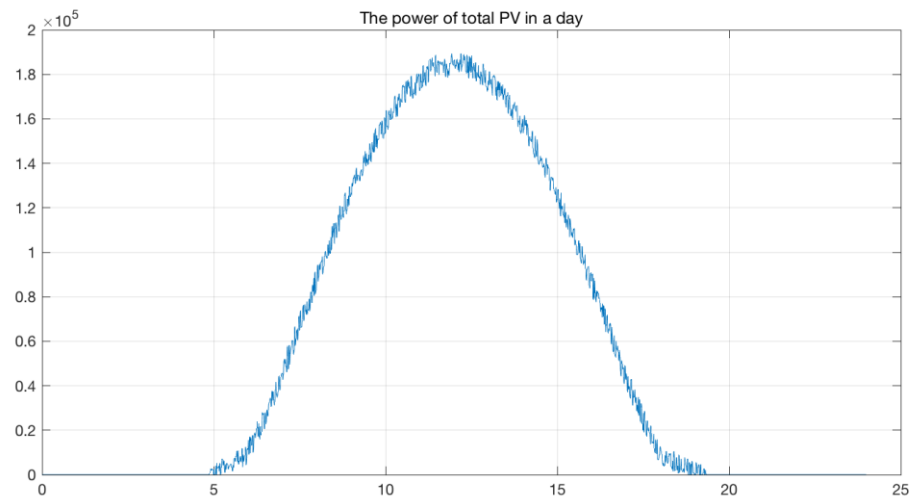
The total energy: $6.935 \times 10^9 \text{ J} = 1926.405 \text{ kWh}$



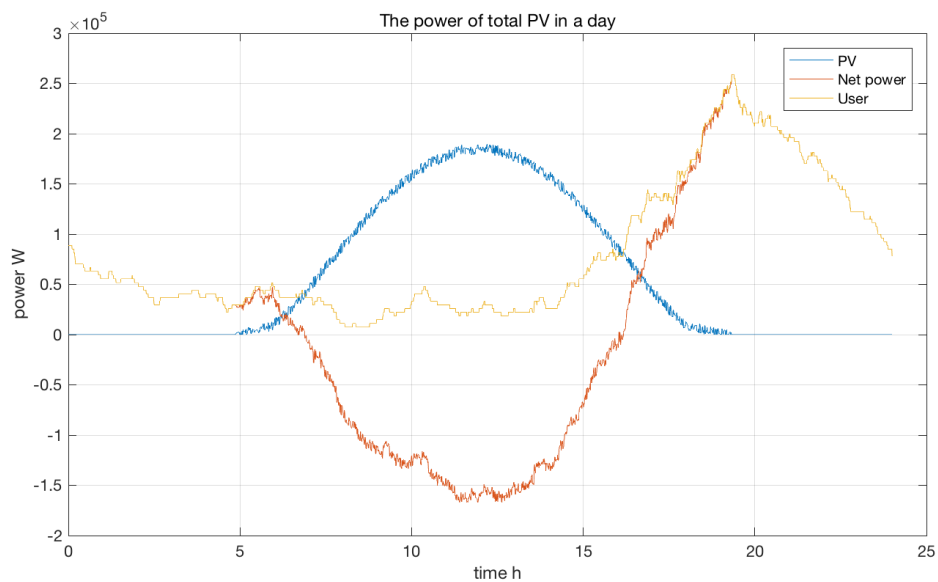
4.2.2 Determine the number of PV

Since we want to combine the grid and the PV together, we set the number of PV as only half of the off-grid case, which is 904 modules, and then we analyze how much energy is required from the grid. Here's the plot of power of

PV:



The total energy produced by PV is $5.0323 \times 10^9 \text{ J} = 1397.9 \text{ kWh}$.
The following figure shows the variation of net power in a day.



After a day, the net energy is $1.9039 \times 10^9 \text{ J} = 528.86 \text{ kWh}$, which means the solar energy is insufficient.

4.2.3 Operating Strategy

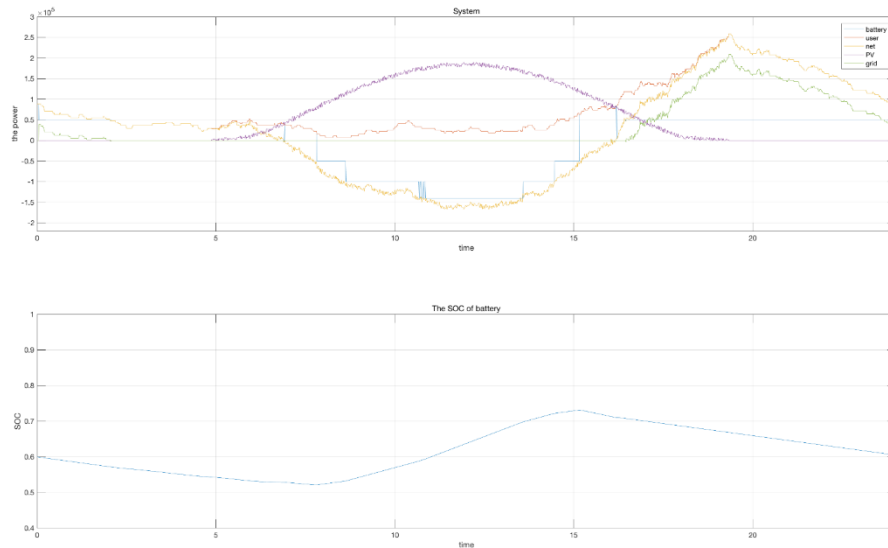
Since we need to use the energy from the grid, the strategy of using the external energy is essential to minimize the cost and lost.

In fact, there are four questions we need to answer at first:

1. Can we use the external electricity to charge our battery?
2. Can we sell the surplus solar energy to grid?

Q1: Can we use the external electricity to charge our battery?

The answer to this question might be obvious but here is the thing. Following the previous off-grid case, we can regard external electricity as auxiliary energy source that fills the shortage passively and we don't use the external electricity to charge the battery in the daytime. Here is the simulation result:



We use the same charging strategy and the external electricity is used at night to fill the shortage. In this case, if we don't use the energy from grid, the sum of external energy consumed is $3.117 \times 10^9 \text{ J} = 865.99 \text{ kWh}$.

The drawback is evident. First, we can't fully use the solar energy in the daytime because of the charging pattern. Second, in order to fill the shortage, we have to use large amount of electricity at the peak hour when the electricity's price is the highest.

- In summary, using the external electricity to charge the battery is necessary.

Q2: Can we sell the surplus solar energy to grid?

In this case, the sum of solar energy that the system can produce is 1397.9 kWh which is less than the sum of expected consumption, 1926.405 kWh. So, our objective is to maximize the utilization of solar energy instead of selling it.

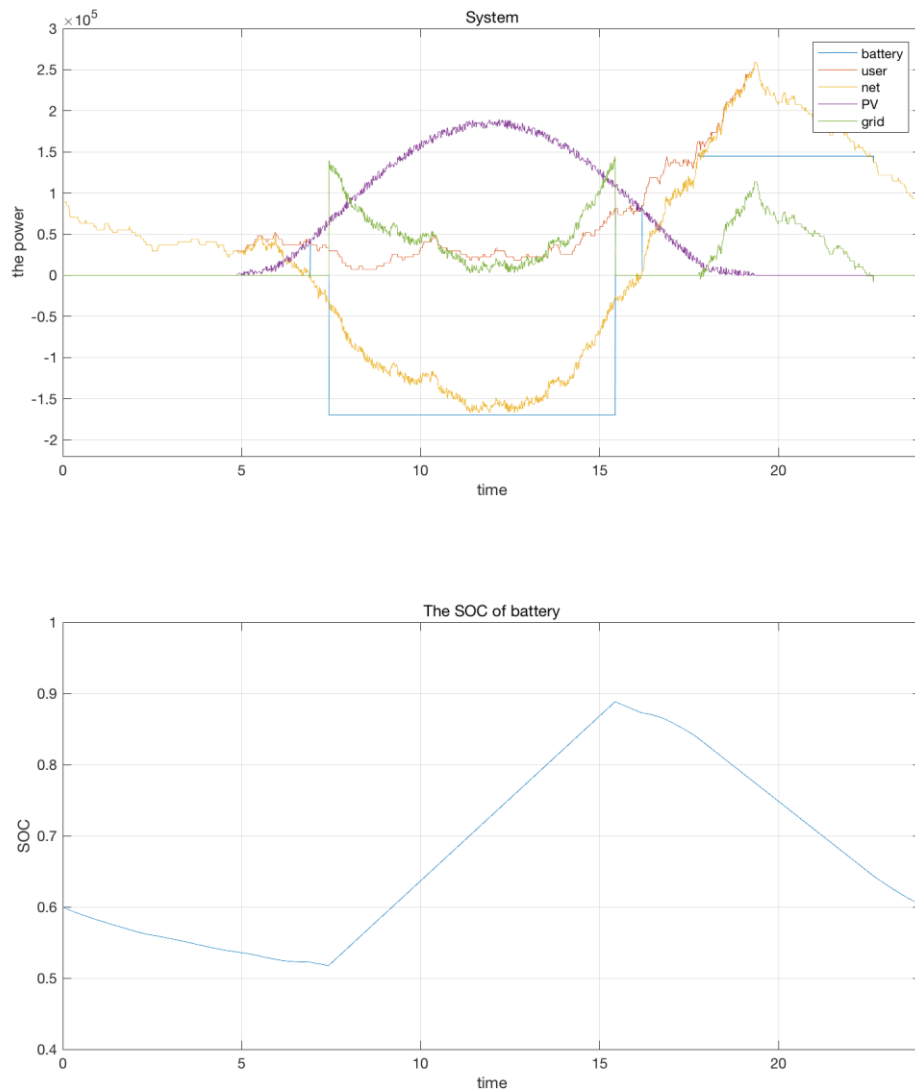
- In summary, selling surplus solar energy to grid is not practical.

Following these two principles, we can design the optimal strategy to operate the system. In the next part, we propose two operable strategies then compare them in terms of economic factor.

1) Strategy one – Charge with high power:

The first strategy follows the same ideas of not charging by grid. Since the energy we get from PV is not enough, we use the grid to charge the battery simultaneously. The power of charging is fixed to the maximum power of PV and here is the result of

simulation:



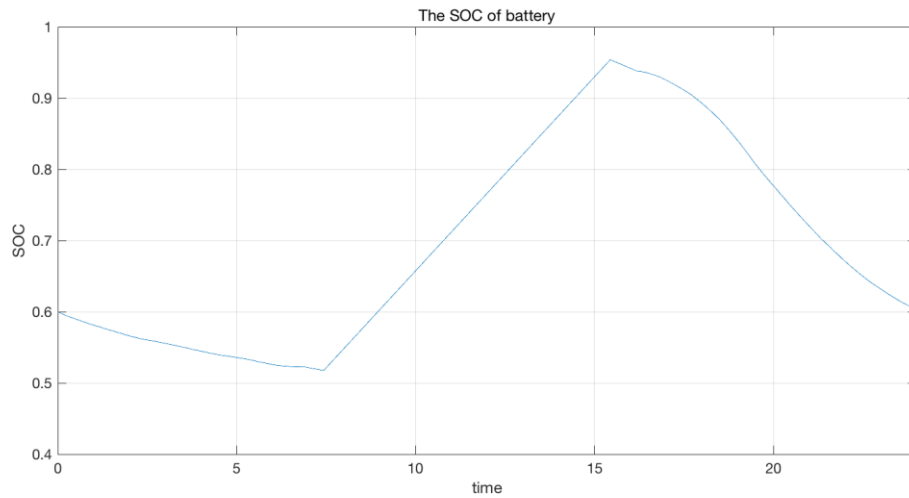
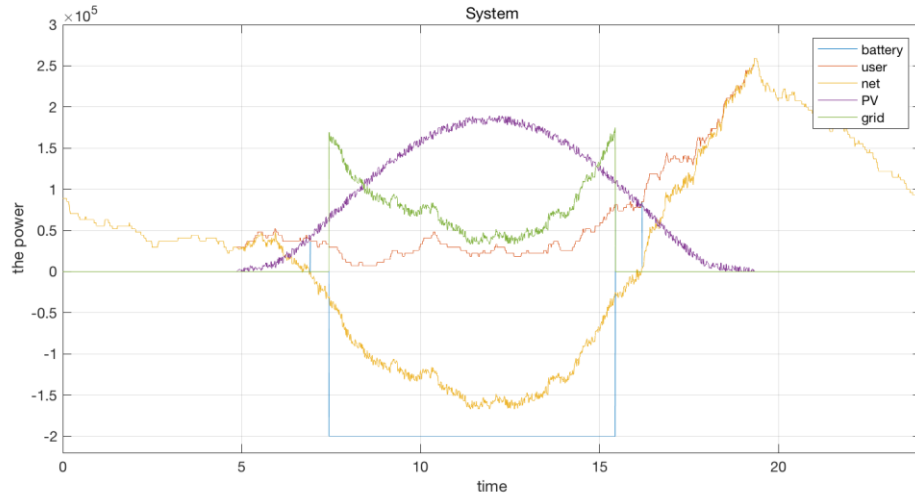
Though the battery is charged with a constant high power, the amount of storage is still not enough to satisfy the needs at the peak hour. It also needs to use the external energy to fill the shortage. The sum of external energy consumed is $2.2947 \times 10^9 \text{ J} = 637.41 \text{ kWh}$.

There are two advantages of this strategy. Firstly, it requires less capacity of battery, which it only needs 80% of capacity in the off-grid case, so the fixed cost can be reduced. Secondly, it uses relatively low level of charging current (0.02C), which is good for the battery's lifespan.

However, the disadvantages are also evident. It also has to use the external power at the peak hour.

2) Strategy two – Charge with low power:

In order to solve the problem of using external energy at the peak hour, we propose the second strategy that using larger power to charge the battery in the daytime. Here is the result of simulation:



We increase the power of charging to 200kW and in this case, the storage of battery can satisfy all the needs during the peak hour. The sum of external energy consumed is $2.2948 \times 10^9 \text{ J} = 637.44 \text{ kWh}$, which is identical to the strategy one.

Comparing to the strategy one, the advantage is that not using external energy at the peak hour. The cost of electricity can be reduced. However, the disadvantage is that it requires using high level of charging current and it also needs larger amount of capacity to store the energy.

4.2.4 Conclusion

- Total consumption: 1926.405 kWh
- Solar energy: 1397.9 kWh
- Number of PV: 904
- External energy from grid: 637.4 kWh
- Capacity of battery: 3.3077×10^5 Ah
- Number of battery (100 Ah, 12V): 3308

3. Case 3: Load-management with battery

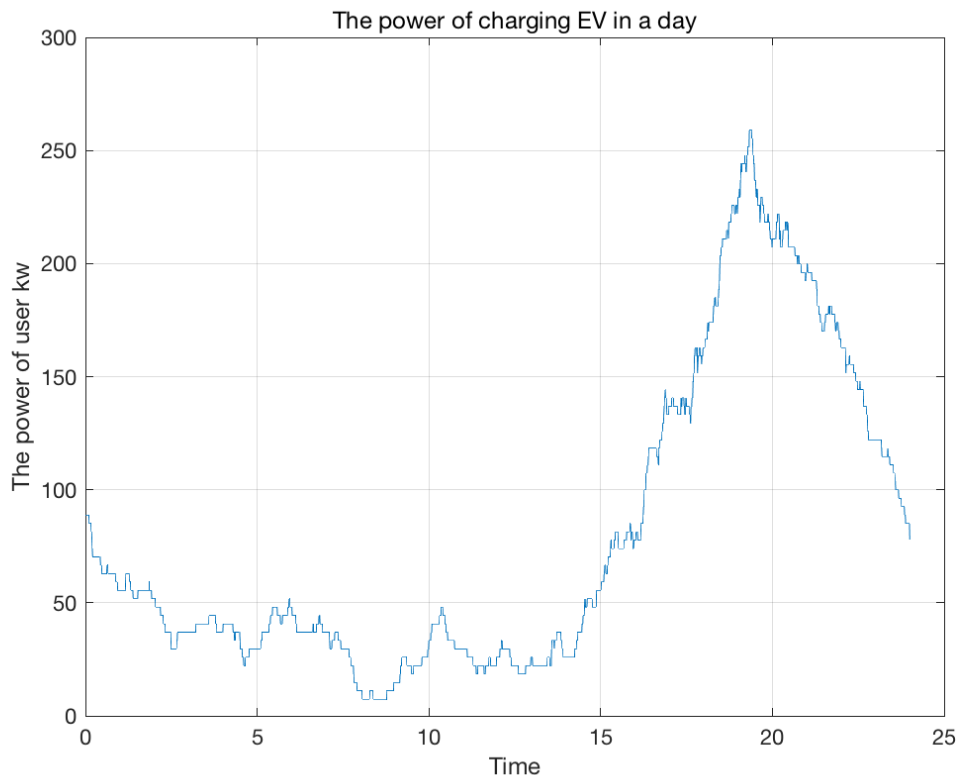
This is the base of analysis because it only has three parts: Grid, User and Battery. We are interested in how to use the load management to minimize the cost of operating the electrical parking lot. The load management here means to use the battery to transfer the load at the peak hour to the off-peak hour.

$$E_{\text{user}} = E_{\text{grid}}$$

4.3.1 Determine the demand of power consumption

For a residential area that has around 100 EVs

The total energy: $6.935 \times 10^9 \text{ J} = 1926.405 \text{ kWh}$



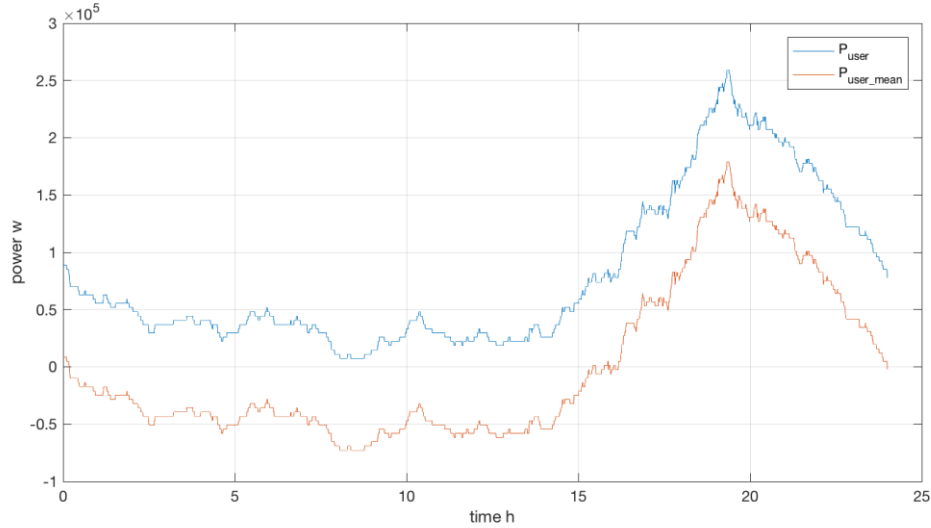
4.3.2 Determine the number of battery

Battery unit:

- Combination method: 3S 50P (150 cell)
 - Rated capacity: 100Ah

- Working voltage: 11.1V
- Standard charged voltage: 12.6V
- Standard charged current: $0.2C = 20A$
- Maximum charged current: $1C = 100A$
- Maximum discharged current: $0.2C = 20A$

According to the user's scenario, we can find the average of P_{user} is **80.233 kW**. The following figure is the variation of P_{user} – $P_{user_average}$:



So, the amount of we want to transfer is the integral of the positive part of $P_{user} - P_{user_average}$.

The amount of storage is **$2.4617 \times 10^9 J = 683.80 kWh$**

Using the previous formula:

$$C = \frac{E_{total} \eta \times \beta \times U_{working}}{683.80 kWh \times 0.85 \times 0.5 \times 11.1V} = 1.4495 \times 10^5 Ah$$

Where:

C is the capacity of battery, η is the rate of energy loss, β is the depth of discharging. So, we need at least $N_{bat} = \frac{C}{C_{unit}} = 1450$ modules of battery in parallel.

4.3.3 Charging strategy

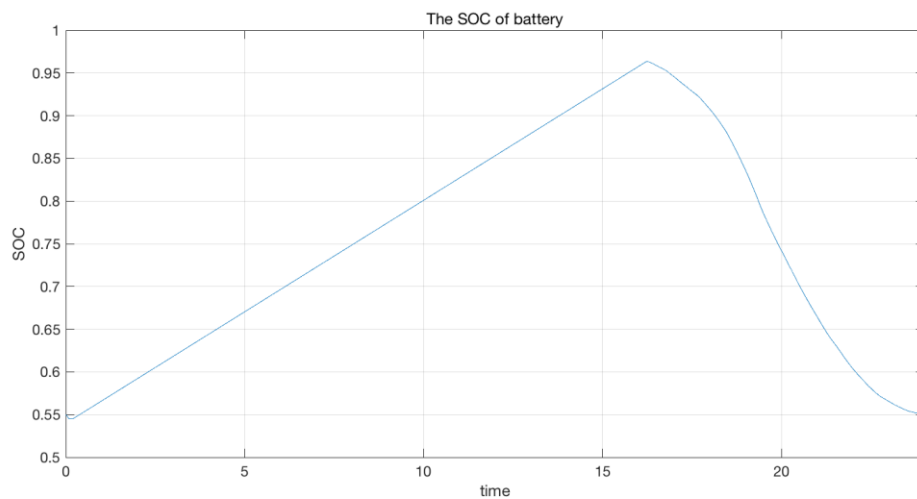
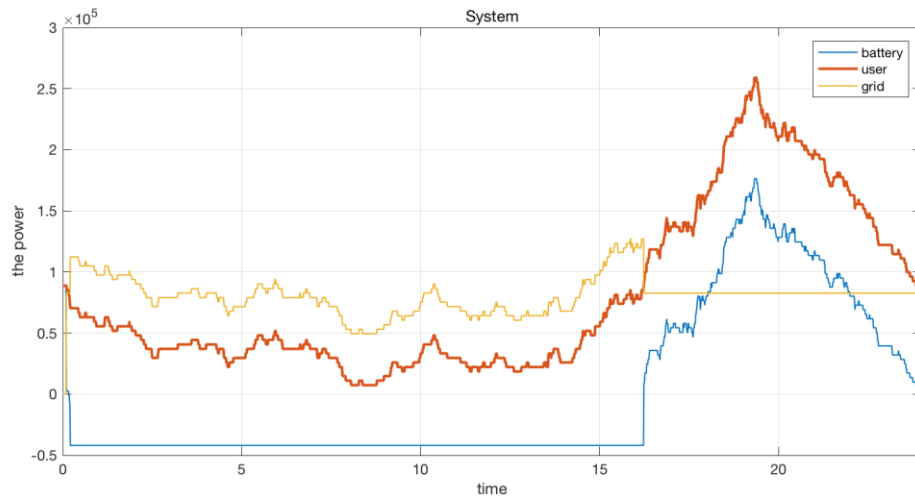
In this case, the strategy of charging battery is very simple. When the required power of user is below the mean value, we use the external energy to charge the battery. In the meantime, we also use the grid to supply user's consumption.

$$P_{grid} = P_{charge} + P_{discharge}$$

When the power of user is above the mean value, we use the battery and grid at the same time to supply the user. At this time, we fix the power of grid at the mean value of user's power.

$$P_{user} = P_{grid} + P_{discharge}$$

And here is the result of simulation:



As we look the evolution of SOC is a closed cycle, the system is viable. The total energy from grid is $6.9395 \times 10^9 \text{ J} = 1927.6 \text{ kWh}$, which is closed to the amount of consumption.

The advantage of this strategy is that it uses relatively low capacity of battery. And the structure of system is simple, which means its operating cost is low.

4.3.4 Conclusion

- Total consumption: 1926.405 kWh
- Capacity of battery: $1.4495 \times 10^5 \text{ Ah}$
- Number of battery (100 Ah, 12V): 1450

5 Evaluation of the economic feasibility

In order to provide an intuitive comparison between different charging strategies and to verify the influence brought by different installation of PV to our system, the economic effect should be taken into account as a primary index. According to several researches concerning the cost evaluation for renewable energy production and storage system, we decide to choose the levelized cost of electricity as the evaluation standard and apply it to our concepts to exam their feasibility.

5.1 Levelized cost of electricity (LCOE)

The levelized cost of electricity (*LCOE*) is the main economic index for evaluating various power generation technologies, which is equal to the unit-cost electricity over the lifetime of a generating asset. LCOE can be seen as the price at which energy must be sold to break even over the lifetime of the technology. It gives comparison of different technologies.

The general equation for LCOE is given in Equation 1. It is essentially the lifecycle cost of the system be divided by the lifetime energy production of the system.

$$\text{LCOE} = \text{Lifecycle cost (€ or \$)} / \text{Lifetime energy production (kWh)} \quad (1)$$

We apply the “discounting” method, in which the stream of (real) future costs and (electrical) outputs identified as C_t and E_t in year t are discounted back with discount rate r , to a present value (PrV).

$$\text{LCOE}_{\text{discount}} = \text{PrV (Costs)} / \text{PrV (Output)} = \frac{\sum_{t=1}^n C_t / (1+r)^t}{\sum_{t=1}^n E_t / (1+r)^t} \quad (2)$$

5.2 Methology

5.2.1 LCOE for PV

The energy produced by PV is either directly used to meet the need of users (E_{direct}), otherwise, or stocked in the energy storage system for some later utilization (E_{surplus}).
 $\text{EPV} = E_{\text{direct}} + E_{\text{surplus}} \quad (3)$

Therefore, the LCOE for PV can be written as follows:

$$\text{LCOE}_{\text{PV}} = C_{\text{pv_surplus}} + C_{\text{pv_direct}} \text{EPV}_{\text{surplus}} + \text{EPV}_{\text{direct}} \quad (4)$$

We obtain the precise calculation of the LCOE for a PV system by expressing every part of cost and taking into account the degradation of system:

$$\text{LCOE} = \frac{I_t + \sum_{t=1}^n \frac{O_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^n \frac{E_t}{(1+r)^t}} = \frac{I_t + \sum_{t=1}^n \frac{O_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^n \frac{S_t(1-d)^t}{(1+r)^t}} \quad (5)$$

I_t : the initial investment (an one-off payment)

E_t : the energy generated in a given year

S_t : the rated energy output per year

$1-d$: the degradation factor which decrease the energy with time

M_t : maintenance costs
 O_t : operation costs
 F_t : interest expenditures

5.2.2 LCOE for the energy storage system (ESS)

The formula proposed here allows us to compare between different types of storage technologies.

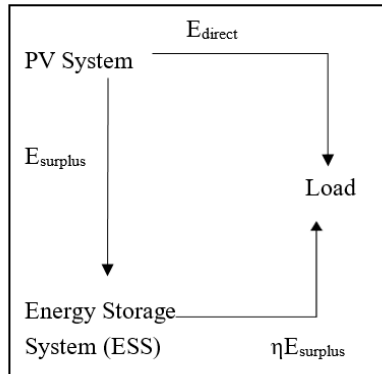
$$LCOS = I_0 + \sum_{t=1}^n CESSt (1+r)^{-t} \sum_{t=1}^n EESSt (1+r)^{-t} \quad (11)$$

I_0 : the initial investment, including the capital cost and the installation cost, which are all one-off investment

- $CESSt$: total operation and maintenance cost at year t
- $EESSt$: total energy output at year t

5.2.3 LCOE for the whole system (PV + ESS)

The figure below shows that the energy generated by solar panels is divided into 2 parts. One part is to supply the load directly, while the other part is stored in the energy storage system (ESS). The net energy output of the ESS needs to take account of the roundtrip efficiency η .



The total energy produced by the system is the energy output of ESS and the energy directly delivered to the load by PV.

Therefore for the PV+ESS system, we obtain such relation:

$$LCOE_{system} = \sum_{t=1}^n C_{system} (1+r)^{-t} \sum_{t=1}^n E_{system} (1+r)^{-t} = C_{pv_surplus} + C_{pv_direct} + C_{ESS} E_{pv_direct} + E_{ESS} \quad (12)$$

We elaborate the calculation for every term:

$$C_{pv_surplus} = (C_{cap_pv} + C_{inst_pv} + \sum_{t=1}^n C_{O\&M_pvt} (1+r)^{-t}) * NPV_{surplus} \quad (8)$$

$$C_{pv_direct} = (C_{cap_pv} + C_{inst_pv} + \sum_{t=1}^n C_{O\&M_pvt} (1+r)^{-t}) * NPV_{direct} \quad (9)$$

$$C_{ESS} = C_{cap_ESS} + \sum_{t=1}^n C_{O\&M_ESSt} (1+r)^{-t} \quad (10)$$

$$E_{pv_direct} = \sum_{t=1}^n (E_{direct} * 365) (1 - D_{pv}) (1+r)^{-t} \quad (11)$$

$$E_{ESS} = \eta \sum_{t=1}^n (E_{surplus} * 365) (1 - D_{ESS}) (1+r)^{-t} \quad (12)$$

C_{cap} : Capital cost per unit

C_{inst} : Installation cost per unit

$C_{O\&M}$: Operation and maintenance cost per unit

η : Roundtrip efficiency of ESS

D : Degradation rate

r : Discount rate

$N_{pvsurplus}$: the number of units of PV panels for producing surplus energy

$N_{pvdirect}$: the number of units of PV panels for producing direct energy

* In our simulation program, E_{direct} , $E_{surplus}$ and E_{ESS} are calculated by day, so here when we evaluate its value economic performance, we multiply it by 365. For the very rough prototype of our LCEO, we simply assume the E_{direct} , $E_{surplus}$ and E_{ESS} are relatively stable. Here we take the same daily production for the whole year, as an initiatory approximation.

Notice

Since we don't isolate particularly the PV to produce the energy directly used and the energy stored, so we combine the two parts together, which means

$$NPV_{total} = NPV_{surplus} + NPV_{direct} \quad (13)$$

$$C_{pv} = C_{pvsurplus} + C_{pvdirect} = (C_{Cap_pv} + C_{Inst_pv} + \sum_{t=1}^n C_{O\&M_pvt} (1+r)^t) * NPV_{total} \quad (14)$$

The O&M cost of batteries and PV depends on the size of our system, which we measure by the maximum puissance.

$$C_{O\&M_pvt} = C_{O\&M} * P_{pv_max} \quad (15)$$

$$C_{O\&M_batt} = C_{O\&M} * P_{bat_max} \quad (16)$$

5.3 Parameters in our scenario

To calculate the LCOE of our system, the parameters that we should take into account are as follows:

	PV	ESS (Batteries)
Model	Kyocera kc200gt	(SB100) 12V 100AH Lithium Ion Battery
Capital cost (C_{cap})	300 (\$/unit)	1,300 (\$/unit)
Installation cost (C_{inst})	3 (\$/kW)	N/A
O&M cost ($C_{O\&M}$)	6 (\$/unit/year)	10 (\$/kW/year)
System lifetime (n)	N/A	20 years
Roundtrip efficiency (η)	N/A	~85%
Degradation rate	5%	1%
Discount rate	7%	

Table 1 Parameters for our case

5.3 Economical effects of different strategies

5.4.1 Case 1. Off-grid system

$LCOE_{system} = C_{pv_surplus} + C_{pv_direct} + C_{ESS} E_{ESS} + E_{pv_direct} = C_{pv} + C_{bat} E_{bat} + E_{pv_direct}$ (15)

$CO\&M_{pvt} = P_{pv_max} \cdot COM$ per kW (16)

$C_{bat} = C_{Cap_bat} + \sum_{t=1}^n CO\&M_{ESSt} (1+r)^t$ (17)

with (11) + (12) +

(14)

Different amounts of energy needed in our calculation are obtained in our simulation program.

Changing charging puissance	
Number of PV	1807
Number of batteries	3104
Total energy produced by PV	2794.16(kWh/day)
Directly used energy from PV	410.97 (kWh/day)
Total energy issued from batteries	1515.4 (kWh/day)
Max puissance of PV	380(kW)
Max puissance of batteries	250(kW)

20 years	1.2857 €/kWh
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5.4.2 Case 2. Grid-connected system

5.4.2.1 Batteries with high capacity

In this case we reduce the number of PV to half, which may cause the insufficiency of energy provided by PV. Thus we will probably need the grid to supply some extra energy. The price of energy from the grid differs in different time periods. The price in the south region of France is as follows:

	Peak hours	Off-peak hours
Time	07h00 - 14h00 17h00 - 0h00	02h00 - 07h00 14h00 - 17h00
Price	0.156 €/kWh	0.127 €/kWh

Energy price in the south of France

Extra energy are extracted from the grid to supply the batteries, then batteries are discharged during high price period. So with batteries of high capacity, there is literally no direct energy offer from the grid to users.

We assume that the ratio of (energy provided in high price period) / (energy provided in low price period) is stable around the year.

Equations applied to this case:

$$LCOE_{grid_con} = C_{pv} + C_{ESS} + C_{gridEPV} + E_{bat_output} + E_{grid} \quad (18)$$

$$E_{bat_output_t} = \eta * (E_{pv} * 365) * (1 - D_{bat})^t * (1 + r)^t \quad (19)$$

$$E_{grid_t} = E_{conso} - E_{batt} \quad (20)$$

$$E_{bat_output} = \sum_{t=1}^n E_{bat_output_t} \quad (21)$$

$$E_{grid} = \sum_{t=1}^n E_{grid_t} \quad (22)$$

$$C_{grid} = \sum_{t=1}^n CO\&M_{ESSt} * E_{gridt} * (1 + r)^t \quad (23)$$

Number of PV	904
Number of batteries	3308
Daily need of energy for users	1926.405 kWh
Daily total production of PV	1397.9 kWh
Daily total direct used energy from PV	335.08 kWh
Daily total storage in batteries	1591.3 kWh
Daily energy from the grid	471.6 kWh high price 165.8 kWh low price period
Max puissance of PV	190 kW
Max puissance of batteries	250 kW
Cost	
Daily cost for grid	94.63 €
LCOE	0.2518 €/kWh

5.4.2.2 Batteries with low capacity

Since the batteries are fixed at a lower capacity, so sometimes we need the grid to directly offer energy to users.

Number of PV	904
Number of batteries	3308
Daily need of energy for users	1926.405 kWh
Daily total production of PV	1397.9 kWh

Daily total direct used energy from PV	335.08 kWh
Daily total storage in batteries	1351.1 kWh
Daily energy from the grid	514.8kWh high price 122.6 kWh low price period
Max puissance of PV	190 kW
Max puissance of batteries	180 kW
Cost	
LCOE	0.3007 €/kWh
Daily cost for grid	95.88 €

5.4.3 Case 3. Grid-battery system

All the energy coming from the grid is either directly provided to users, or stored in batteries to be used later. So the sum of the energy extracted from the grid is always equal to the user's need.

$$LCOE_g = C_{bat} + C_{grid} E_{bat_output} + E_{grid_dir} \quad (24)$$

$$E_{bat_t} = \eta * (E_{batday} * 365) (1 - D_{bat})^t (1 + r)^t \quad (25)$$

$$E_{grid_t} = E_{con_year} - E_{batt} \quad (26)$$

$$E_{bat_output} = \sum_{t=1}^n E_{bat_t} \quad (27)$$

$$E_{grid} = \sum_{t=1}^n E_{grid_t} \quad (28)$$

$$C_{grid} = \sum_{t=1}^n C_{grid_unit} * E_{grid_t} (1 + r)^t \quad (29)$$

Battery + Grid (20 years)

Number of PV	904
Number of batteries	1450
Daily need of energy for users	1926.405 kWh
Daily total storage in batteries	672 kWh
Daily total energy from the grid	1234.4 kWh high price 693.2 kWh low price period
Max puissance of batteries	180 kW
Cost	
LCOE	0.1798 €/kWh
Daily cost for grid	280.61 €

5.4 Comparison

Grid-off	Grid-connected		Grid+Battery
	High capacity	Low capacity	
1.0270€/kWh	0.2518€/kWh	0.3007€/kWh	0.1798 €/kWh

Therefore, after considering all the cases, we find that there is no significant economical profit compared with the price of using electricity directly from grid. However, we provide a feasible method of load-management with the help of battery. Because the initial investment of the system is relatively expensive in these years, the implementation of solar panels on a large scale is not feasible economically/. But with the popularization of the renewable energy and more developed technology of energy storage system, we believe that there is still a large potential market for the renewable system in the future.

6 Conclusion

1. From the physical model, we can observe the great potential of renewable resource, which provides us with a great amount of energy. If we make full use of the
2. According to our analysis, using renewable as economical as we imagined. Even the average price is higher than the price of EDF. It's due to the costly initial investment. Nowadays the price of solar panels and batteries are still relative high, which make the economic advantages of renewable energy only evident in a long term. If we think of a short period (5 years or 10 years etc.), the LCOE in our cases would be even higher. Therefore, the renewable energy system seem more profitable for long-term use. But we think that, since this field with great potential becomes more and more recognized and more developments in technologies concerned are put forward, the average cost for the use of renewable energy will reduce. When it's applied on a large scale, it will prove more beneficial.

3. Since our physical model and economical model are still so rough that we've simplified our cases to obtain a prototype by neglecting many factors. In real life, situation will much more complicated with a lot more variations, thus the result we obtain is not very accurate. To calculate the cost, we only consider the cost of PV, batteries and energy cost from EDF, but other parts in our system like converters, cables also require investments. Also, concerning EDF, the price of electricity tend to vary from year to year. Therefore, for a more precise evaluation, we need more predictions.

4. In terms of charging strategies, we can see that by combining the use of solar energy and batteries, we really reach a lower daily cost. This verifies the feasibility of our ideas. But apparently they're not the optimal solutions. As more factors should be taken into account, our strategies still need improvement in order to be more flexible and more adaptive.

7 Acknowledgement

We would like to express our deepest appreciation to all those who helped us to complete this project. A special gratitude we give to our project client, Mr. Baert, whose contribution in stimulating suggestions and encouragement, helped us to continue our project.

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